Strokes for Representing Univariate Vector Field Maps

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Abstract

Particle systems make an excellent tool for creating tracks (which we call strokes) in vector fields. The question addressed in this paper is how such tracks should be made to vary in size and colour in order to reveal properties such as local direction and strength of the field. We find that for strokes that vary from large to small, direction is indicated by the large end. We also find that for strokes that vary in colour, the colour of the background is the most important determinant of perceived direction.

Keywords: Data Display, Vector Fields.

1 Introduction

An early example of the use of line segments to represent vector field data is a 17th century map by Edmond Halley (discussed in Tufte, 1983) which shows trade winds over the Atlantic Ocean (see Figure 1). Halley's elegant pen strokes are shaped like long narrow airfoils oriented to the flow,with the wind direction being given the blunt end. While vector field plots have become more accurate in intervening years, they have also simultaneously become less easily read and less attractive. A standard computer plotting method for displaying vector fields is to provide a regular two dimensional array of line segments which by their orientation display direction and by their length display magnitude. It is also possible to use the density of line segments in order to display an additional field parameter (Lavin and Cerveny, 1987).

Of course, line segments are ambiguous as to direction - hence the common use of arrows which are strokes embellished with arrowheads (Lueptow, 1988). But even arrows may not give the correct impression according to Bertin (1983) who advocates broadening the stroke towards the head of the arrow in order to get the correct impression of direction. A disadvantage of arrows is that the arrowheads often clutter up the map, especially when the line segments are dense and certainly when drawn by computer.

Recently there have been attempts to break away from the simple line segment with or without an arrowhead. Hibbard (1986) used flow lines, generated in a computer graphics system, which are represented by cylindrical pipes twisting through a three dimensional space and rendered in perspective. He also used strokes, whose tails fade to transparency, to great effect.

The Particle Systems technique (Reeves, 1983, 1985) was recently invented to model such phenomenon as fire and clouds. Particle systems have obvious application in providing tools to visualize vector field maps. The essence of the method we use is as follows: We scatter particles on the vector field where they immediately begin to move in the direction indicated by the local field. As the particles move they age, and as they age they may change their characteristics in a number of ways. We define a "stroke" as the trace left by a particle over the course of its life. The purpose of this paper is to report on an attempt to develop guidelines on how to design strokes in order to best reveal properties of the vector field.

Once we depart from the notion of a stroke as a uniform width variable length line segment, a large number of possibilities offer themselves. Strokes may vary in colour or size as they age, or they can vary in colour or size to reflect aspects of the field they are to represent. Moreover, strokes may be made to vary in colour in a variety of different ways. They may be made to vary, for example, in luminance, or in hue, and they may be made to vary cyclically or monotonically. In this paper we present the results of a study designed to examine how people perceive direction and magnitude using some of the simplest strokes.

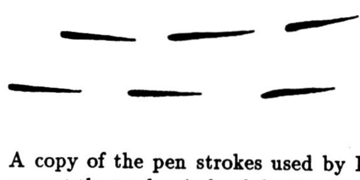

Figure 1. A copy of the pen strokes used by Edmond Halley (1686) to represent the trade winds of the North Atlantic. Halley described the wind direction as being given by "... the sharp end of each little stroak pointing out that part of the Horizon, from whence the wind continually comes ". Halley's map is discussed in Tufte (1983).

1.1 Colour and Size

We decided to study the perception of strokes which change linearly in size, either getting smaller or larger, and strokes which change in colour as they age, either changing from white to black, from black to white, or from red to green. We also investigated strokes which had a constant size and strokes which had a constant colour (black). These strokes were used to display a circular vector field. We asked two basic questions of our observers.

1. In which direction is the vector field oriented? That is, does the flow appear to be clockwise or counter clockwise?
2. How strong is the impression of flow?

Note that we described the images as representing flow to our subjects, but we presume that the results will apply to the perception of other vector fields.

2 Experimental Design

2.1 Stimuli

The stimulus pattern was generated using a synthetic circular field. The field was descibed by

$$\delta x = 0.01 \sin(\tfrac{y\pi}{2})$$
$$\delta y = -0.01 \sin(\tfrac{x\pi}{2})$$

where $\delta x, \delta y$ gives the distance between successive positions of a particle as it traces out a path over the course of its lifetime. Particles aged through 25 steps and then disappeared. To create the stimulus pattern a virtual square was randomly seeded with 150 particles which were allowed to age to extinction. The particles were generated using a uniform random function in a virtual square with lower left hand corner having coordinates (-1.1,-1.1) and uppper right hand corner having coordinates (1.1,1.1). The space in which the particles were generated was clipped to (-1.0,-1.0), (1.0,1.0) and the square was mapped to a 22 by 22 cm window centered on the monitor.

2.1.1 Stroke Shape

The shape of the strokes was achieved by making the particle size a function of the particle's age. Three functions were investigated.

1. Particles could start off having a diameter of 1 mm and linearly increase in size to 4 mm at their death.
2. Particles could maintain the same diameter of 2.5 mm over the course of their lifespan.
3. Particles could start off having a diameter of 4 mm and linearly decrease in size to 1 mm at their death.

2.1.2 Stroke Colour

The colour gradient of a stoke was achieved by making the colour a function of the particle's age. Three functions were investigated.

1. Particles could start off black and change to white using the following function.

   $$L = (age/25)^{2/3}$$

   if we consider L to be luminance that varies over $[0, 1]$. We chose this exponent for our grey scale function because under the display conditions of the experiment (at least with a grey background) this produced the most perceptually linear gradient from black to white.

2. Particles could start off white and change to black using the equation.

   $$L = (1 - age/25)^{2/3}$$

3. Particles could start of red and change to green using a linear interpolation between monitor red and monitor green. The CIE chromaticity coordinates and maximum luminance values (x, y, Y) for the monitor guns are:

	x	y	Y
R	0.610	0.342	15.72
G	0.298	0.588	33.80
B	0.151	0.063	6.14

2.1.3 Background Colour

The colour of the background was set to one of the following three values:

1. The start of the colour gradient as described above (this could be one of black, white, or red).
2. The middle of the colour gradient described above (this could be one of grey or beige).
3. The end of the colour gradient as described above (this could be one of black, white, or green).

The basic design was a three by three by three factorial experiment consisting of all twenty-seven combinations of the above factors. In addition there were three other experimental conditions consisting of each of the three stroke shapes defined above in solid black on a white background. The resulting thirty conditions are summarized in figure 2. Three of the stimulus patterns are illustrated in figure 3.

2.2 Measures

The subject was required to observe thirty trials and record observations about them with respect to the direction and strength. The subject indicated direction by stating either "clockwise" or "counter clockwise". This was a forced choice decision in that the subject was forced to respond with one of the above even if no direction was apparent. Strength of perceived direction was assessed using a five point rating scale (0...4).

Trials were presented to each subject in random order.

Table 1a

Black → White

	Inc	Same	Dec
first	13	11	12
(black)	3.54	2.31	3.15
middle	6	1	1
(grey)	0.07	1.85	2.54
last	0	0	1
(white)	3.61	3.54	3.00

Table 1b

White → Black

	Inc	Same	Dec
first	12	13	13
(white)	3.38	3.00	3.46
middle	11	9	4
(grey)	2.62	0.77	1.00
last	1	0	0
(black)	2.92	2.62	3.31

Table 1c

Red → Green

	Inc	Same	Dec
first	12	12	13
(red)	3.15	2.69	3.46
middle	8	4	0
(beige)	0.46	0.46	2.00
last	1	1	0
(green)	3.00	3.00	3.54

Table 1d

Solid Black

	Inc	Same	Dec
	13	5	1
(white)	3.00	0.00	2.54

4 Results and Discussion

The strongest factor in determining the direction of flow was an interaction between the color of the background and the colour sequence used. The direction of perceived flow was away from the end of the stroke which matched the background colour. These can be determined by examining the top and bottom rows of the Tables 1a, 1b, and 1c which contain a total of 234 observations. Out of these observations only ten deviate from the above rule. Of these deviations five were contributed by a single subject. The effect occurs irrespective of the shape of the stroke and irrespective of the colour sequence.

The effect of stroke shape was studied in the conditions where the strokes were a constant black on a white background. In these cases (see Table 1d) the direction of motion was perceived as towards the larger end of the stroke, no matter which way the stroke was drawn. This finding is consistent with the phenomenological observations of Halley (1686) and of Bertin (1983).

A complex picture emerges when we examine the effects of colour sequences and grey sequences on a neutral background. In the grey scale conditions with a neutral background (center cell in tables 1a and 1b), the subjects tended to find the particles to be moving towards the darker end of the stroke. This is most evident from the constant size trials. However when size is brought into consideration, the tendency of the subjects to perceive direction towards the large end of the stroke would either enhance or conflict with this. Thus when the dark end coincides with the large end of the stroke, a stronger perceived flow rating was obtained compared with the constant size condition. Conversely, if the dark end coincided with the small end of the stroke, a very weak rating was obtained.

The red-green colour gradient on a neutral background also produced some interesting results. It appears that the colour red is the dominating colour. When the large end of the stroke is red, the subjects unanimously agreed on a direction, although did not rate it as strong. In the other two stroke categories, the subjects did not agree on the direction of flow.

The study presented here only begins to tap the possibilities for designing strokes using particle systems. An idea which we are currently exploring is the presentation of more dimensions simultaneously. Thus we can use hue, for example, to represent temperature in a vector field, while value (lightness) represents age. Another idea is to use particle size to represent exaggerated depth in a slice through a three-dimensional vector field.

5 Acknowledgements

We wish to thank Serge Limoges for his preliminary research into the use of particle systems for the representation of flow data.

6 References

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Also, the direction in which the strokes were drawn was determined randomly to be one of clockwise or counter-clockwise.

2.3 Subjects

There were thirteen subjects. Each subject was colour normal according to Ishihara Pseudoisochromatic plates and had (at least) 20/20 vision by a Snellen eye chart.

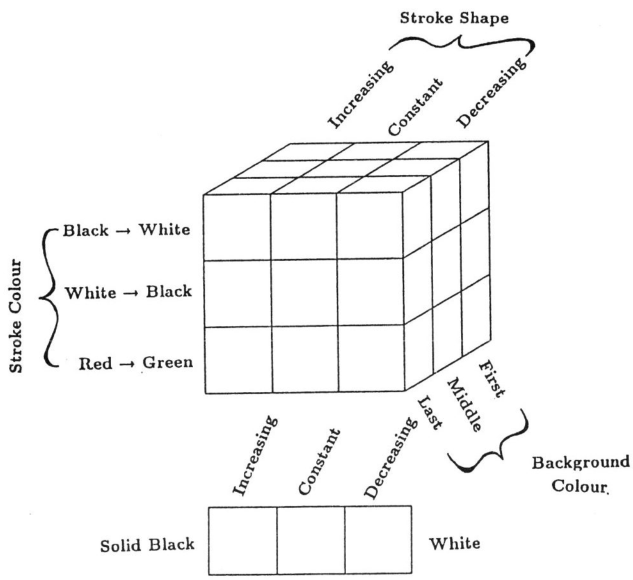

Figure 2. A visual representation of the 3 by 3 by 3 factorial experiment with 3 additional conditions.

3 Results and Discussion

In order to derive a value for the strength of movement which took into account the direction of perceived movement we devised the following metric.

$$\frac{\left|\sum_{i=1}^{13} d_i x_i\right|}{13}$$

where

$$d_i = \begin{cases} 1 & subject_i \text{ matched direction} \\ -1 & subject_i \text{ did not match direction} \end{cases}$$

and x_i represents the rating scale response by each subject. The strength ratings, averaged across subjects, are given in the lower half of each cell in Tables 1a, 1b, 1c and 1d which summarize the results from all thirty experimental conditions. The integer in the upper half of each cell is the total number of subjects out of thirteen who reported that the direction displayed matched the direction in which the strokes were drawn. These tables correspond to planes in Figure 2.

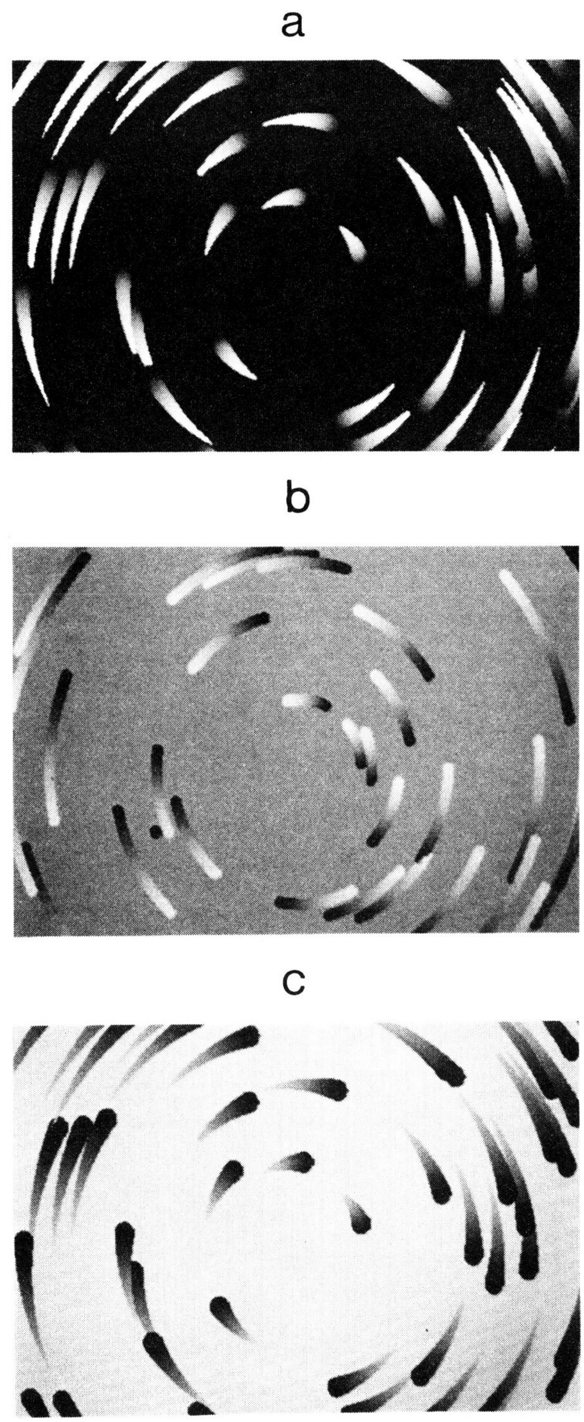

Figure 3. Photographs showing a small portion of each of three of the stimulus patterns. All three utilize the black → white colour sequence. (a) appears on a black background and was constructed using particles which decrease in size. (b) appears on a grey background and was constructed using particles of a constant size. (c) appears on a white background and was constructed using particles which increase in size.

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